Quarterly Technical Progress Report
on Fundamental Hydrodynamics Research
(ONR - Code 12)

1 January 1990 through 31 March 1990

Prepared by Cognizant ARL Penn State
Principal Investigators

Garfield Thomas Water Tunnel
Applied Research Laboratory
The Pennsylvania State University
Post Office Box 30
State College, PA 16804

Telephone: (814) 865-1741

PREFACE

Under the sponsorship of The Office of Naval Research (Code 12) AHR Program, The Applied Research Laboratory of Penn State University performs basic research in hydrodynamics and hydrodynamic noise. The hydrodynamics research conducted under this program falls into two basic thrust areas:

- Turbomachinery

  To develop an improved understanding of the fluid mechanics and acoustics associated with low-speed turbomachines and marine propulsors. To employ this knowledge to the development of improved propulsor and turbomachine design methods.

- Drag Reduction

  To develop fundamental understanding of the mechanisms that cause drag on bodies and surfaces and to explore novel methods to reduce drag.

Under each thrust area, one or more projects are conducted under the direction of the principal investigator who initiated the given task. All tasks are designed to provide results that will improve the scientific understanding of various hydrodynamic phenomena associated with the operation of submerged bodies and surfaces.

This report documents the technical progress realized during the first quarter of FY 90 for the projects currently approved under this program.

TURBOMACHINERY

SUBTASK T1

Title: Turbomachine Internal Flow Definition
(S. A. Abdallah, University of Cincinnati)

BACKGROUND

The internal flow field of a wake adapted turbomachine is dominated by three dimensional and unsteady effects. The three dimensionality of the flow field is demonstrated by the strong secondary flows which have been experimentally measured. The unsteadiness of the flow is due to the interaction of the downstream blade rows with the wakes shed from the upstream blade rows. The development of computational tools to accurately predict these types of flow fields is essential if successful development of high performance turbomachinery is to be achieved.

PROGRESS

1. Publications

The Discrete Continuity Equation in Primitive Variable Solutions of Incompressible Flow, accepted for publication by Journal of Computational Physics, (1990).

2. A three-dimensional code has been completed for steady turbulent flow. The code is used to compute the Wigley parabolic hull for which detailed experimental data is available [1]. The experiments of Sarda [1] were carried out on a 10 ft. long double model suspended by cables in a 5 ft. closed wind tunnel. The measurements were made at a $R_e = 4.50 \times 10^6$ based on the ship length and the free-stream velocity.

The available data include the pressure distribution on the hull measured by surface pressure taps and the mean-velocity components measured by a five-hole pitot probe [2].

Because of the complex geometry of the hull, non-orthogonal curvilinear coordinates are used as shown in Figure [1]. The coordinates are generated numerically using a separate code employing an elliptic type equations of the Poisson type [1].

Numerical results are obtained, first for the inviscid case. These results are then used as initial guesses for the turbulent case. The number of grid points used in the present calculations is (50 x 31 x 16) in the radial-tangential- and axial directions respectively.

Details of the method and detailed comparisons with the experimental data of Sarda [2] are being finalized for a journal publication (Journal of Computations Physics). A sample of the computed results is shown in Figures (2) to (4). Figure (2) shows the mean axial velocity starting from the ship surface ($y^* = 0$) to the freestream. Figure (2) is at $x = 0.967$ which is just upstream of the tail (which is at $x = 1.0$). Figures (3) and (4) show the same velocity component in the near wake ($x = 1.002$) and for the far wake ($x = 1.1$) respectively. The computed results compare very well with the experimental and correctly predict the wake behavior. Patel's results are shown on the same figures. We would like to point out here that the $K-\epsilon$ turbulence model is used in Patel's study, while the Baldwin-Lomax model is used in ours. We believe, however, that our results are much more accurate than Patel's results not because of the different turbulence models used but because of the accurate satisfaction of the discrete continuity equation in our method. For more details about the drawbacks of not satisfying the continuity equation to machine accuracy, the reader is referred to our publication in Section 1.

REFERENCES

1. Ship Stern and Wake Flows: Solution of the Fully-Elliptic Reynolds-Averaged Navier-Stokes Equation and Comparisons with Experiments by V. C. Patel, H. C. Chen and S. Ju. IIHR Report No. 323, (1989).

2. Sarda, O. P. "Turbulent Flow Past Ship Huffs - An Experimental and Computational Study," Ph.D. Thesis, Mech. Eng., Uni lower, (1980).

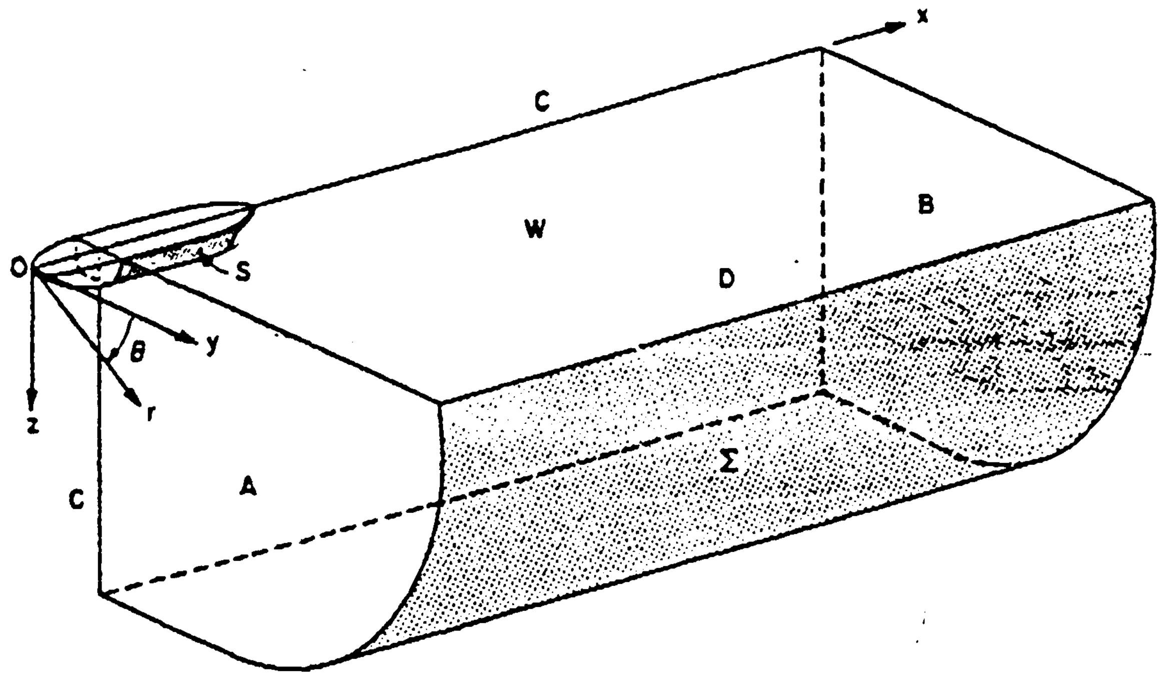

Fig. 1a. Physical solution domain

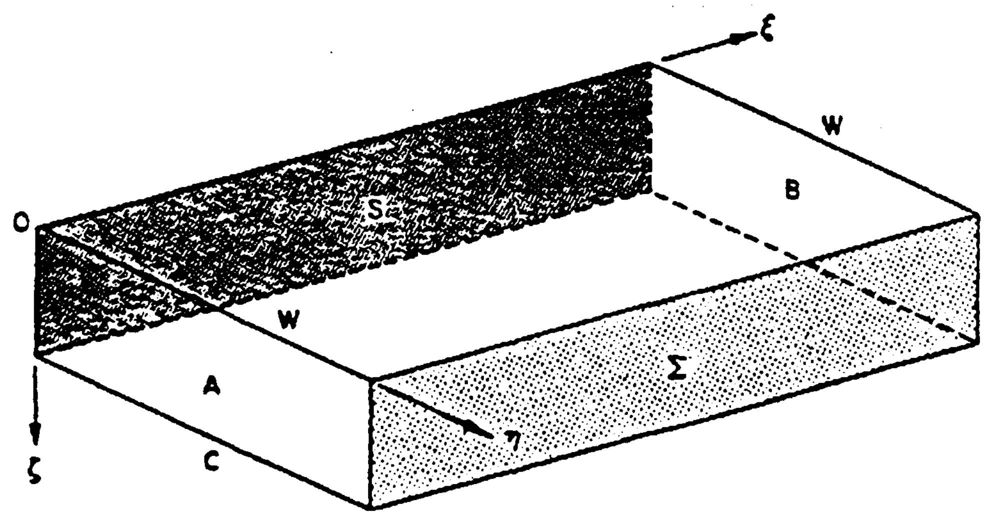

Fig. 1b. Transformed domain

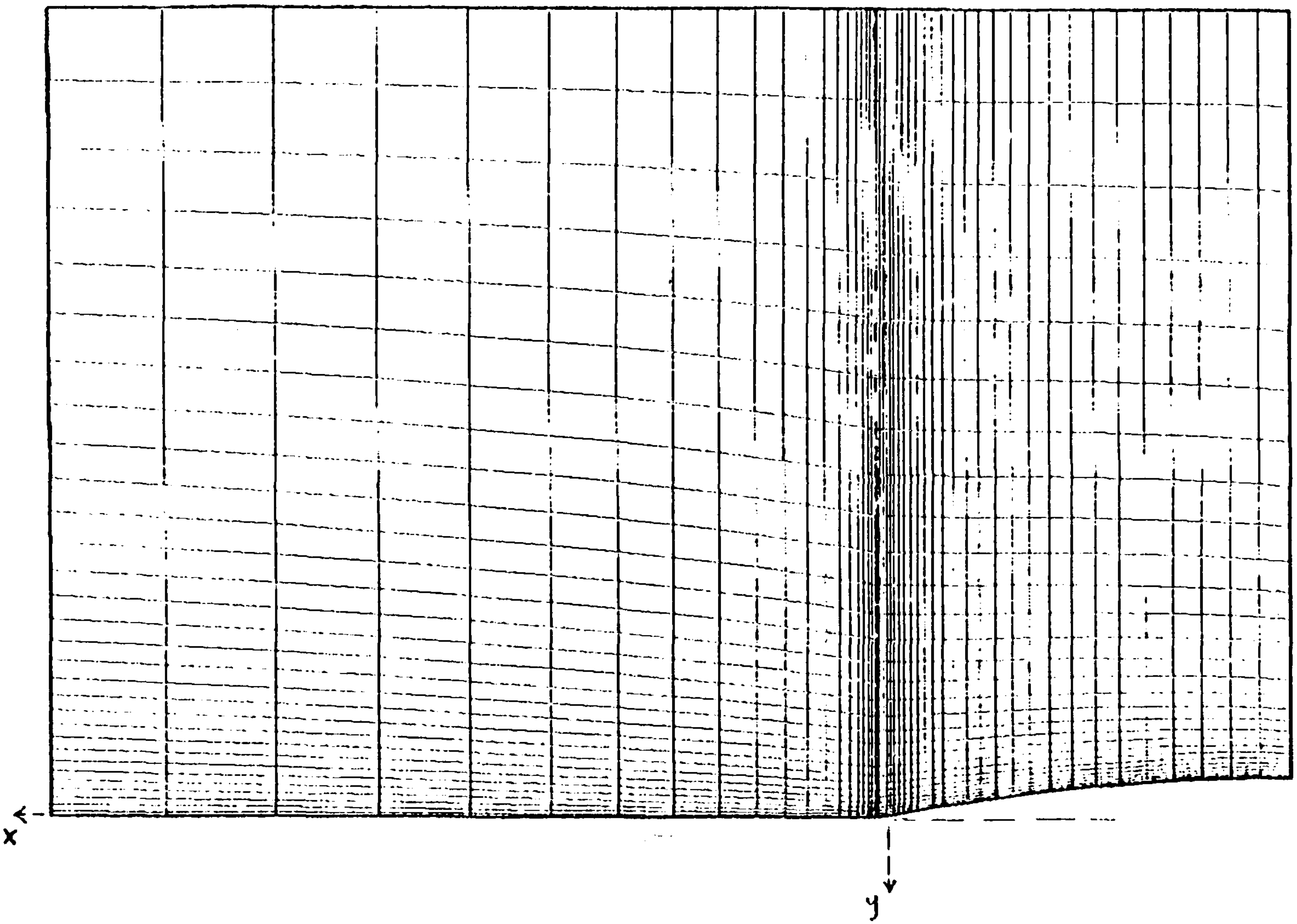

FIG. 1d. WATER SURFACE

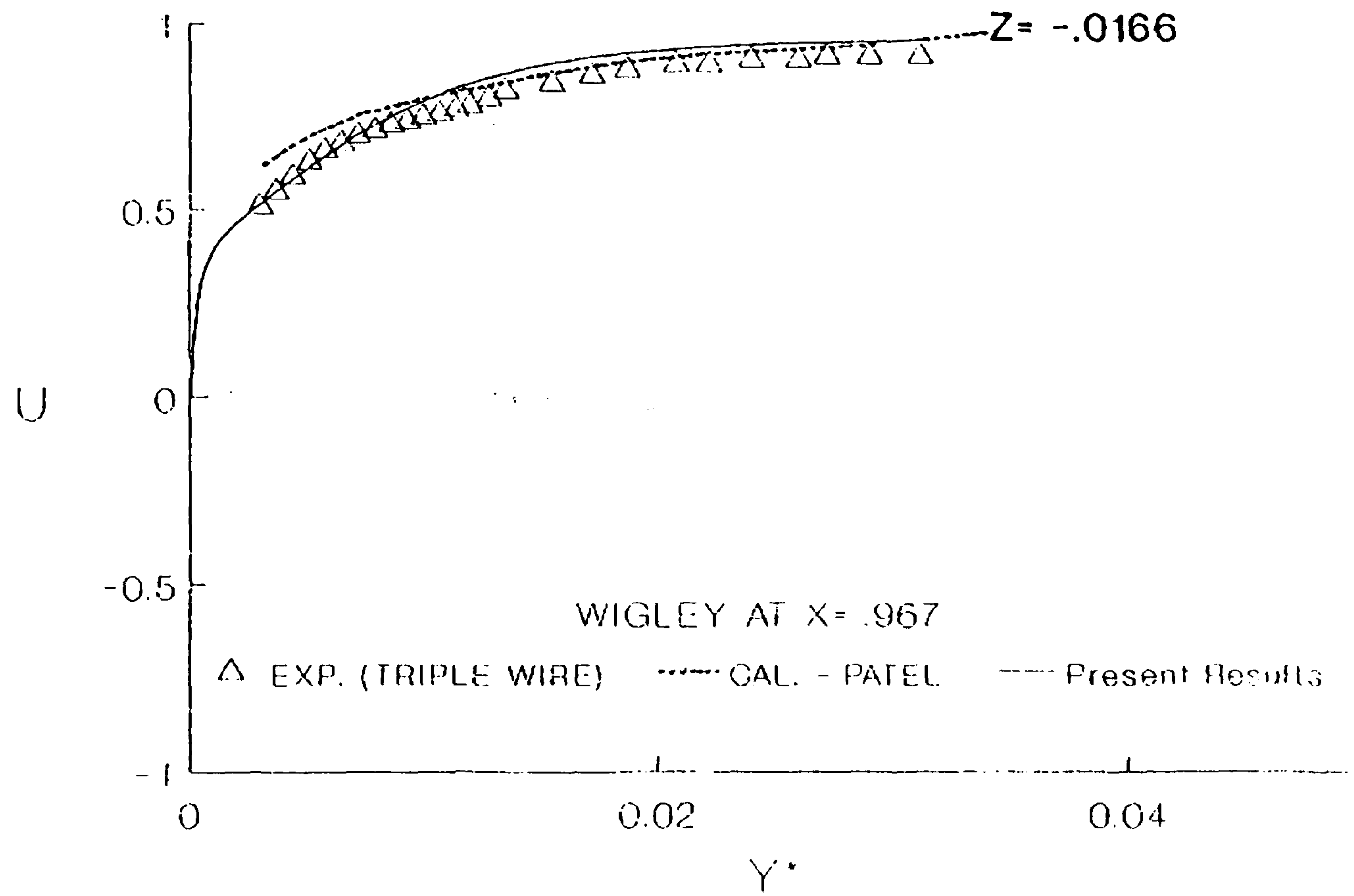
Z= -.0166
1
0.5
0
-0.5
-1
U
WIGLEY AT X= .967
Δ EXP. (TRIPLE WIRE)
CAL. - PATEL
Present Results
0
0.02
0.04
Y*

FIG. 2.

WIGLEY AT X = 1.002 (Z=0.)

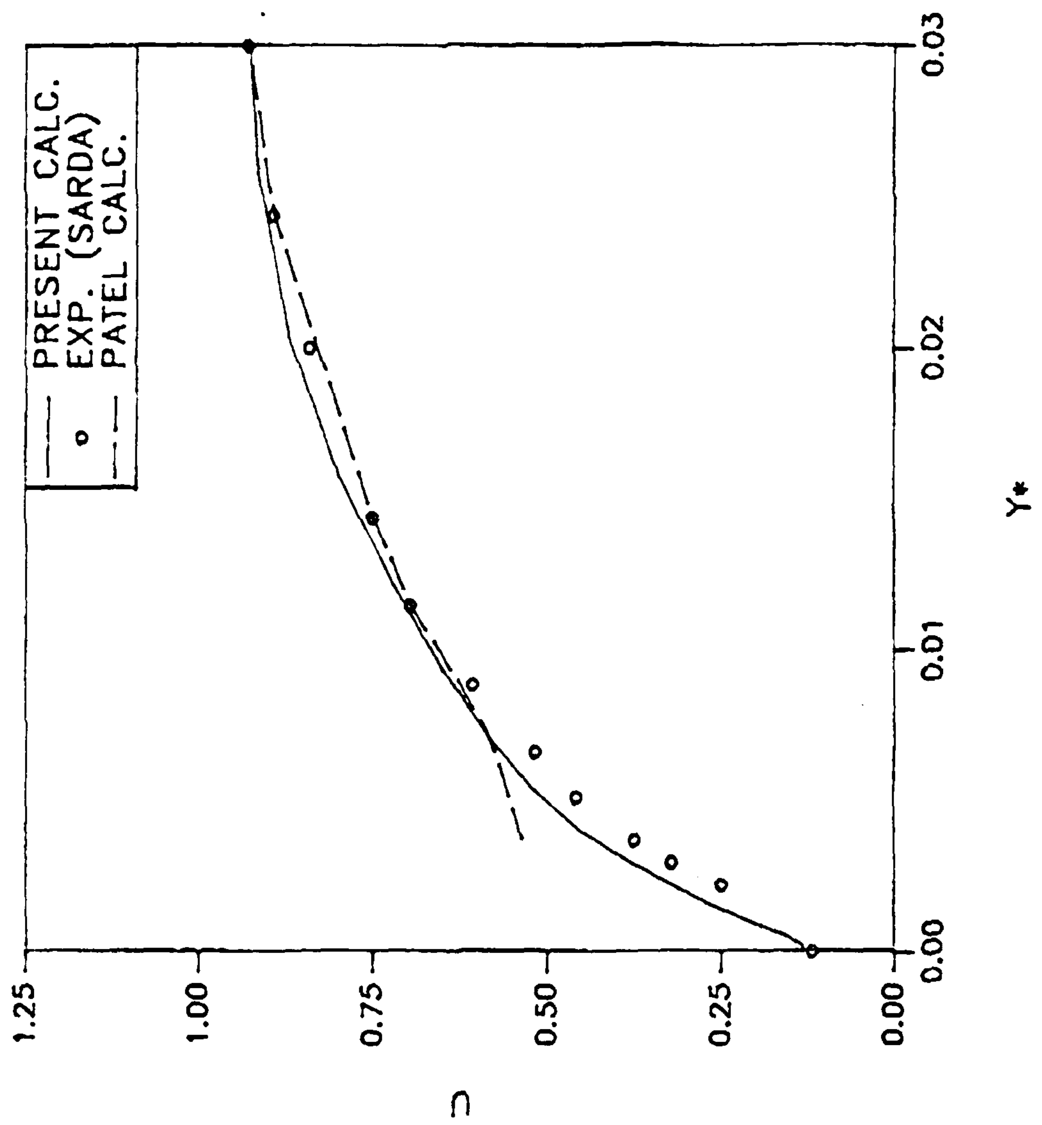

FIG. 3.

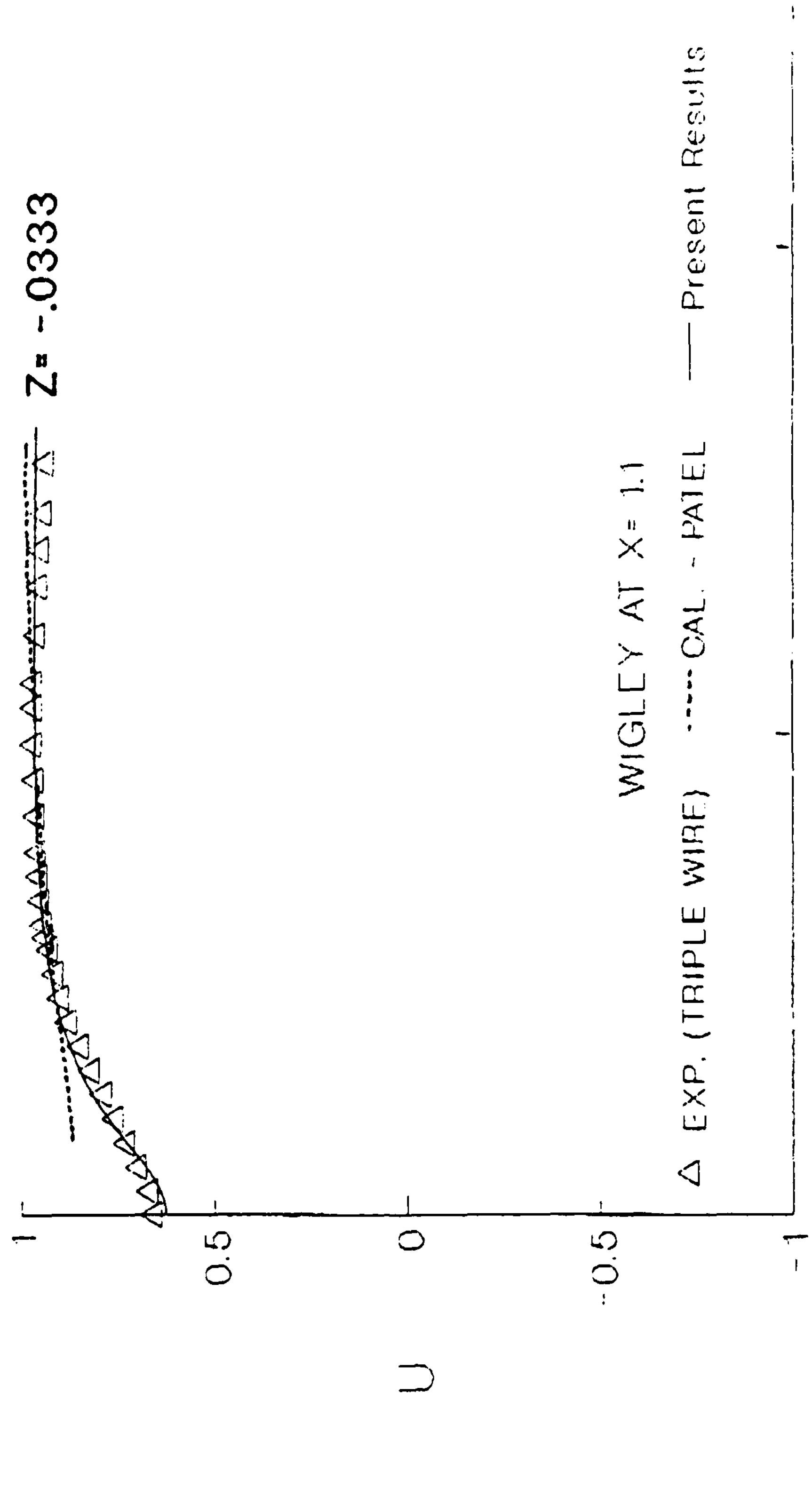
Z= -.0333
WIGLEY AT X= 1.1
Δ EXP. (TRIPLE WIRE) ----- CAL. - PATEL —— Present Results
U
Y'
1
0.5
0
-0.5
-1
0
0.02
0.04

FIG. 4.

DRAG REDUCTION

SUBTASK DR1

Title: Turbulent Spot Generation by Freely Suspended Particles in a Flat Plate (H. L. Petrie and P. J. Morris)

BACKGROUND

Laminar flow control (LFC) has been an attractive technology for many years but premature transition, induced by particles in the fluid, has prevented its successful hydrodynamic implementation. Although an extensive amount of experimental work and analysis has examined the transition induced by various types of roughness elements and intermittent disturbances such as sparks, basic questions regarding the mechanisms for transition induction by freely suspended particles still remain unanswered. The subject experimental and analytic study of particle induced transition is concerned with these issues and is entering the ninth month of activity.

Heated body LFC experiments have demonstrated clearly the degradation of LFC performance due to freestream particles. However, a detailed explanation of this phenomenon has not been developed. Experiments by Lauchle, et al. [1], observed that nearly neutrally buoyant particles of sufficient size caused turbulent spots on an LFC heated body when seeded into the freestream. However, these particles failed to generated spots when injected through a dye port at the nose of the body. If these particles did not migrate away from the wall significantly while accelerating around the nose, then freestream seeded particles must act on the boundary layer with a different mechanism than the wall injected particles. This suggests that the dynamics of crossing streamlines and possibly wall impact may be crucial to spot formation. In support of this, Hall [2], observed that transition could be induced when a spherical particle supported by wire was pulled into the wall even though, once fixed to the wall, the particle was too small to induce a turbulent spot.

PROGRESS

During this reporting period, we have concentrated on defining and calculating the boundary layer flow field over the flat plate model. In addition, we have developed the equation of motion for the particle. This will be used to calculate the particle trajectory for a range of particle properties and release points to be considered in the experiments. Details of the progress in these two areas are given below.

To determine the trajectory of a particle freely released in a fluid, the basic velocity field (u,v) must be computed first. For a

uniform freestream, first-order boundary layer theory gives a zero vertical velocity outside the boundary layer. However, the first-order inner solution gives a finite positive vertical velocity at the edge of the boundary layer. Hence, second-order boundary layer effects have to be taken into account, using the theory of match asymptotic expansions. For a flat plate, the first order solution and the second order solution due to displacement thickness is given by the composite stream function $\psi(x,y;R)$:

$$\psi_{composite} = \frac{\sqrt{2x}}{\sqrt{R}} f_1\left(\frac{\sqrt{R}y}{\sqrt{2x}}\right) - \frac{\beta_1}{\sqrt{R}}[\Re\sqrt{2(x+iy)} - \sqrt{2x}]$$

where R is Reynolds number of the flow, and denotes the real part of a complex function.

Therefore, the velocity components are given by,

$$U = f_1'\left(\frac{\sqrt{R}y}{\sqrt{2x}}\right) - \frac{\beta_1}{\sqrt{2R}} Re\left[\frac{i}{\sqrt{x+iy}}\right]$$

$$V = -\frac{1}{\sqrt{2Rx}} f_1\left(\frac{\sqrt{R}y}{\sqrt{2x}}\right) + \frac{y}{2x} f_1'\left(\frac{\sqrt{R}y}{\sqrt{2x}}\right) + \frac{\beta_1}{\sqrt{2R}}\left[Re\left(\frac{1}{\sqrt{x+iy}}\right) - \frac{1}{\sqrt{x}}\right]$$

These profiles have been calculated for R = 2.5 X 10^5 at x = 0.5 and x = 1.0 and are shown in Figures 1-3.

Once the basic velocity field is computed, the particle trajectory can be determined as follows:

For a spherical particle of radius a*, its motion through a viscous fluid is governed by the equation,

$$\rho_p^* V_p^* \frac{d\bar{V}_p^*}{dt^*} = V_p^*(\rho_p^* - \rho_f^*)\bar{g} - \rho_f^* V_p^* \frac{d\bar{V}_f^*}{dt^*} - \frac{1}{2}\rho_f^*(\bar{V}^* - \bar{V}_p^*)|\bar{V}^* - \bar{V}_p^*|C_D A_p^* -$$
$$\frac{1}{2}\rho_f^*[\bar{k} \times (\bar{V}^* - \bar{V}_p^*)]|\bar{V}^* - \bar{V}_p^*|\bar{C}_L A_p^* - \frac{1}{2}\rho_f^* V_p^*\left(\frac{d\bar{V}^*}{dt^*} - \frac{d\bar{V}_p^*}{dt^*}\right) -$$
$$6A_p^*\sqrt{\frac{\rho_f^*\mu^*}{\pi}} \int_0^{t^*} \left[\frac{d\bar{V}^*}{d\tau^*} - \frac{d\bar{V}_p^*}{d\tau^*}\right] / \sqrt{t^* - \tau^*}\, d\tau^*,$$

where V_p^* = particle volume = $\frac{3}{4}\pi a^{*3}$ and A_p^* = particle surface area = $4\pi a^{*2}$

The various terms in this equation is:
LHS : Mass of the particle multiplied by its acceleration
RHS_1: Buoyant force on the particle
RHS_2: Force due to the pressure gradient in the fluid surrounding the particle
RHS_3: Drag force on the particle
RHS_4: Lift force on the particle
RHS_5: Force required to accelerate the added mass
RHS_6: Basset force on particle, which dominates during the initial acceleration

In nondimensional variables

$$t = \frac{t^* U_\infty^*}{L^*}$$
$$\vec{V} = \frac{\vec{V}^*}{U_\infty^*}$$
$$a = \frac{a^*}{L^*}$$

the particle trajectory equation becomes

$$\frac{1}{2} + \frac{\rho_p}{\rho_f}\frac{d\vec{V}_p}{dt} = -\left(\frac{\rho_p}{\rho_f} - 1\right)\frac{1}{Fr}\vec{j} + \frac{3}{2}\frac{d\vec{V}}{dt} + \frac{3C_D}{8a}(\vec{V} - \vec{V}_p)|\vec{V} - \vec{V}_p| + \frac{3\vec{C}_L}{8a}[\vec{k} \times (\vec{V} - \vec{V}_p)]|\vec{V} - \vec{V}_p|$$
$$+ \frac{9}{2a\sqrt{\pi R}}\vec{I}_B$$

where Fr = Froude number $= U_\infty^{*\,2}/(g^* L^*)$ R = Reynolds number $= U_\infty^* L^*/\nu^*$

$\vec{I}_B$ = Basset integral $= \int_0^t \left[\frac{d\vec{V}}{d\tau} - \frac{d\vec{V}_p}{d\tau}\right] / \sqrt{t - \tau}\, d\tau$

It should be noted that the lift coefficient in the trajectory equation has a vector form. This is because the coefficient depends on the gradient of the fluid velocity in the direction normal to the particle trajectory.

The system of equations for the trajectory is completed by specifying the position vector $\vec{r}_p$, where,

$$\frac{d\vec{r}_p}{dt} = \vec{V}_p$$

For flow along a horizontal flat plate the component equations are

$$\frac{dx_p}{dt} = U$$
$$\frac{dy_p}{dt} = V_p$$

$$(\frac{1}{2} + \frac{\rho_p}{\rho_f})\frac{dU_p}{dt} = \frac{3}{2}\frac{DU}{Dt} + \frac{3C_D}{8a}(U - U_p)\Delta q + \frac{3C_{Lx}}{8a}(V - V_p)\Delta q + \frac{9}{2a\sqrt{\pi R}} I_{Bx}$$
$$(\frac{1}{2} + \frac{\rho_p}{\rho_f})\frac{dV_p}{dt} = -(\frac{\rho_p}{\rho_f} - 1)\frac{1}{Fr} + \frac{3}{2}\frac{DV}{Dt} + \frac{3C_D}{8a}(V - V_p)\Delta q + \frac{3C_{Ly}}{8a}(U - U_p)\Delta q + \frac{9}{2a\sqrt{\pi R}} I_{By}$$

where

$$\Delta q = [(U - U_p)^2 + (V - V_p)^2]^{1/2}$$
$$I_{Bx} = \int_0^t \left[\frac{DU}{D\tau} - \frac{dU_p}{d\tau}\right] / \sqrt{t_\tau}\, d\tau$$
$$I_{By} = \int_0^t \left[\frac{DV}{D\tau} - \frac{dV_p}{d\tau}\right] / \sqrt{t_\tau}\, d\tau$$

The integrand of the Basset term is singular at the upper limit $t=\tau$. To overcome this singularity, a change of variable may be used which allows the trajectory equation to be written in a simple form:

$$\vec{A}_N = \vec{B}_N + C_N \vec{I}_{B_N} \quad \text{at time } t_N$$

where

$$\vec{A} = \frac{d\vec{V}_p}{dt} - \frac{D\vec{V}}{Dt}$$
$$\vec{B} = -(\frac{\rho_p}{\rho_f} - 1)\frac{2}{Fr} + 2\frac{D\vec{V}}{Dt} + \frac{3C_D}{4a}(\vec{V} - \vec{V}_p)\Delta q + \frac{3C_L}{4a}[k \times (\vec{V} - \vec{V}_p)]\Delta q$$
$$C = \frac{9}{a\sqrt{\pi R}}$$
$$\vec{I}_{B_N} = -\sqrt{t_N}\,\Delta\phi_2 \vec{A}_N - \sqrt{t_N}\,\vec{K}$$

where $\vec{K} = (\Delta\phi_2 + \Delta\phi_3)\vec{A}_{N-1} + (\Delta\phi_3 + \Delta\phi_4)\vec{A}_{N-2} + \ldots + \Delta\phi_N \vec{A}_1$

where $\phi^2 = 1 - \tau/t$

Thus $\vec{I}_B$ can be eliminated and the particle acceleration at t_N can be found:

$$(\frac{d\vec{V}_p}{dt})_N = \vec{A}_N + (\frac{D\vec{V}}{Dt})_N$$

where

$$\vec{A}_N = \frac{\vec{B}_N - C\sqrt{t_N}\,\vec{K}}{1 + C\sqrt{t_N}\,\Delta\phi_2}$$

An empirical expression exists for C_D as a function of the particle Reynolds number. A similar empirical relationship for $\vec{C}_L$ is being sought based on experimental studies of freely suspended particles in Poiseuille flow.

Experiments are to be conducted in a low turbulence open channel flow loop facility of the Aerospace Engineering Department at Penn State. Channel assembly and test plate installation have just begun and this will be the primary effort of activity for the next quarter. The channel turbulence management section requires some work yet, but our initial evaluation experiments requires that this section is not in place.

The particle trajectory code has been developed to the point where it can now be used to evaluate trajectories of particles for various specific gravities, diameter, and release position. Particles materials include polystyrene, nylon, delrin, teflon, and brass. Specific gravities are, approximately, 1.05, 1.17, 1.42, 2.17, and 8.59 for these materials. Preliminary results with the trajectory analysis predicts a high degree of sensitivity to the specific gravity. Although the various plastic balls are termed "precision" quality, there is some variability in diameter for a given size. The specific gravities have been estimated and seem to vary also. For instance, nylon specific gravities for the particles we have range from 1.16 to 1.19. As a result, methods of determining the specific gravity of each particle are being considered. The trajectory code will be used to estimate whether the effects of such variability in diameter and specific gravity are substantial enough that we would even be able to notice the difference experimentally.

We are considering releasing particles from rest from a probe for the cases where the particles fall into the boundary layer. The analysis indicates the history or Basset term can be significant for a period after release as the particle accelerates but that the term diminishes quickly.

PLANS

The assembly of the channel will continue and then flowfield evaluation with commence. Initial experimental work will be concerned with flow quality evaluation. The goal of this work is to determine a configuration of the flow conditioning section that is sufficient to quell the large disturbances upstream of it. Following this, the test plate sidewall suction slots and tail will be adjusted. This requires both flow visualization and boundary layer surveys. An LDV is available and we are also considering hot-wires. However, we are not now set-up to calibrate hot-wire probes for the expected range of velocities.

During the next reporting period we will be using this analysis to predict the particle trajectories for a variety of specific gravities and release points and conditions. These properties will be chosen to match the anticipated experimental values. In addition, we will examine the sensitivity of the particle's trajectory to small changes in the particle properties or release position.

Formulation of the initial value problem for particles at arbitrary locations will proceed. Application of the wave packet analysis will first consider fixed particle cases.

REFERENCES

1. Lauchle, G. C., Petrie, H. L., and Stinebring, D. R., "Effects of Particles on the Delayed Transition of a Heated Body," ARL Technical Memorandum 86-213.

2. Hall, W. R., "Interaction of the Wake from Bluff Bodies with an Initially Laminar Boundary Layer," AIAA Journal, V5, N8, pp. 1386-1392.

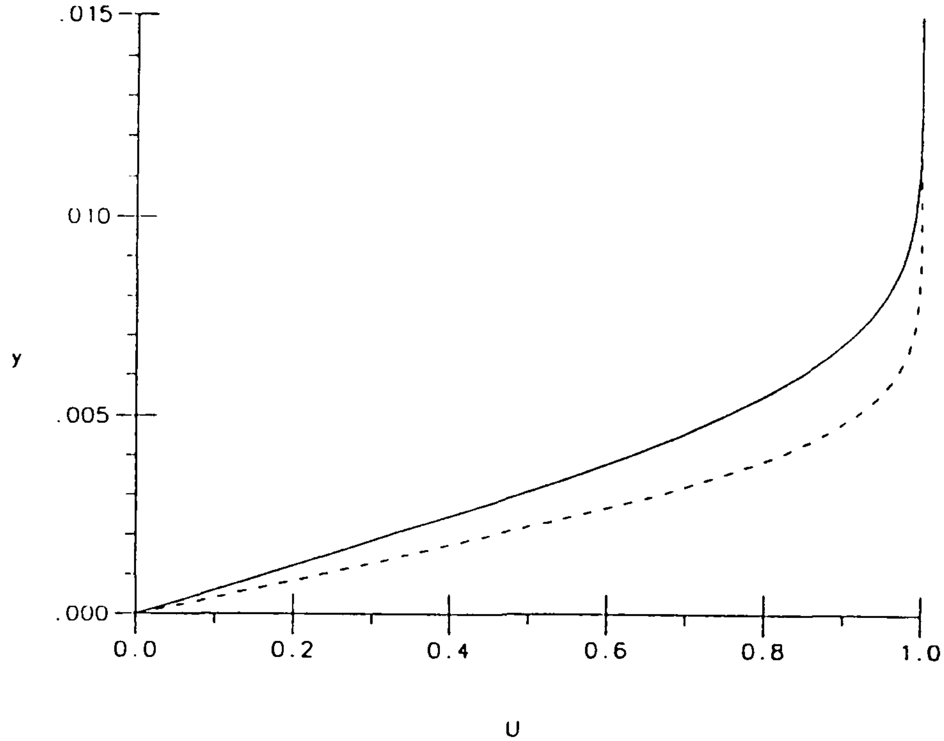

Fig. 1. Streamwise velocity profile. – – –, $x = 0.5$; ——, $x = 1.0$.

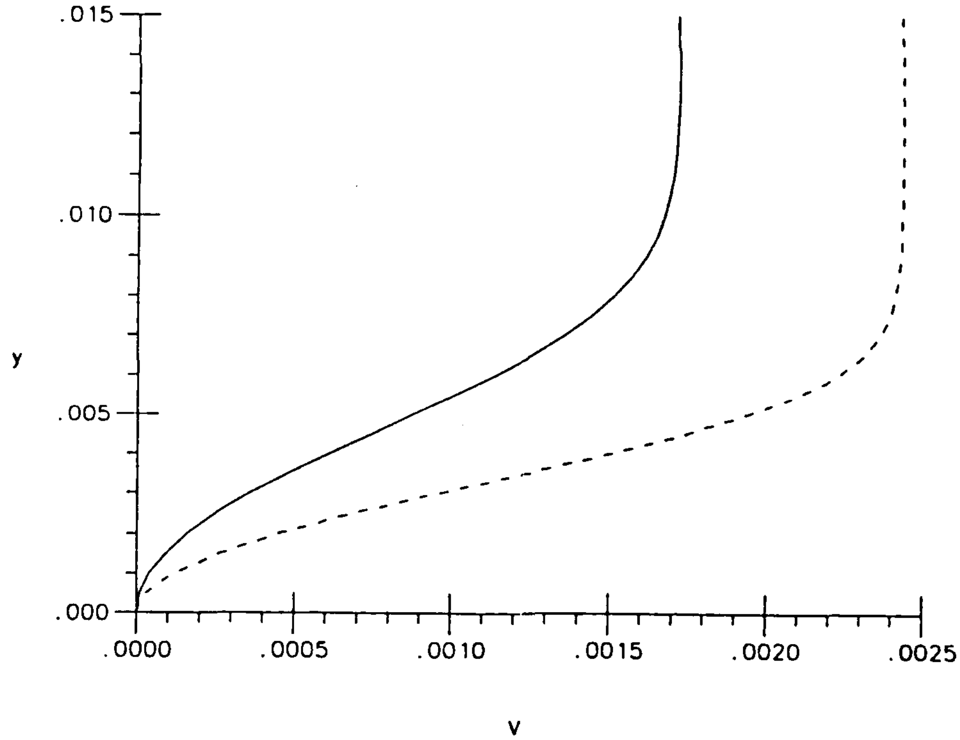

Fig. 2. Normal velocity profile in the boundary layer. – – –, $x = 0.5$; ——, $x = 1.0$.

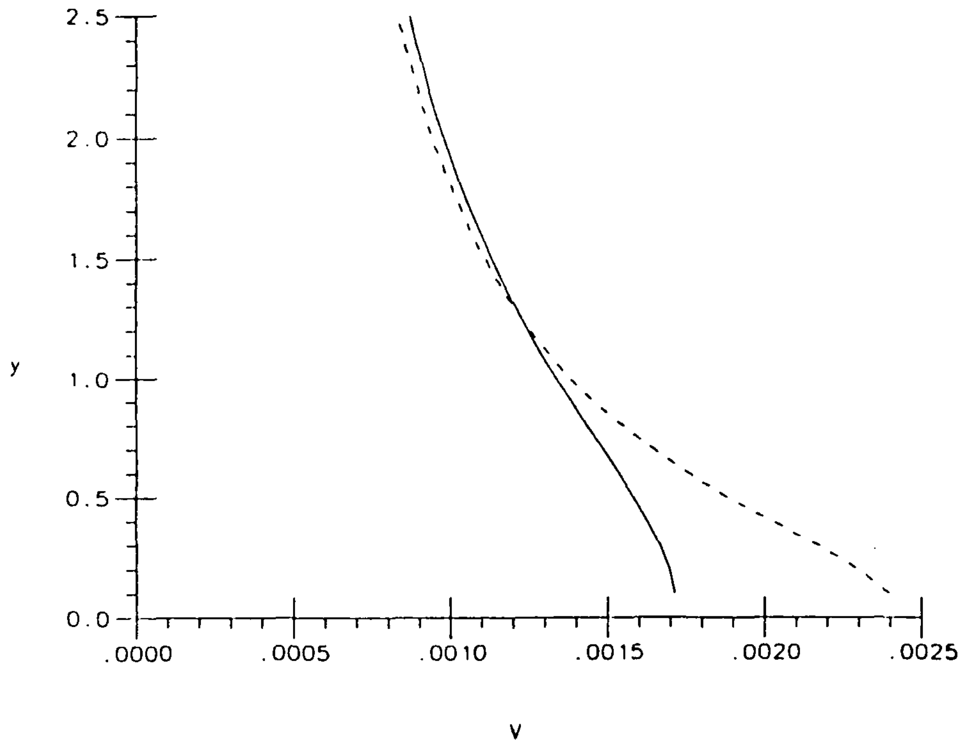

Fig. 3. Normal velocity profile outside the boundary layer. — — —, $x = 0.5$; ——, $x = 1.0$.

SUBTASK DR2

Title: Microbubble Injection in Axisymmetric Flows (S. Deutsch)

BACKGROUND

It has been demonstrated that the injection of gas to form microbubbles in a liquid turbulent boundary layer on a flat plate at nominally zero pressure gradient can reduce skin friction drag by as much as 90% locally. The extension of these results to submerged axisymmetric bodies is the subject of the task.

PROGRESS

A publication based on an extensive set of local skin friction measurements has been accepted (with revision) by the Physics of Fluids. Major results covered in the paper include the fact that the persistence of the phenomenon on an axisymmetric body is the same as that on a flat plate and that the poor performance of microbubble drag reduction at low speeds is a result of a buoyancy driven instability that removes bubbles from the boundary layer.

We are continuing our study of the effect of pressure gradient. We have repeated our integrated skin friction measurements and LDV studies and have measured the pressure gradient on the body with and without bubble injection. Although data analysis is continuing, it appears that the earlier drag reduction data is repeatable and that injection of gas does not change the pressure gradient on the body. Relative levels of drag reduction would appear then to be correct, independent of the effect of pressure gradient on the balance results. Our earlier conclusions that an unfavorable pressure gradient led to higher levels of drag reduction and the prospect of early separation, while a favorable gradient led to much lower levels of drag reduction would appear to be confirmed.

We have begun simple computations of the flow field over the axisymmetric body for the zero, adverse and favorable pressure gradient cases. These computations, which employ the measured pressure gradients, will give us test of the reliability of the absolute values of balance results in a pressure gradient.

Analysis of LDV data has shown that the axisymmetric body we are using is probably not seeing the same boundary layer growth as the body documented by Deutsch and Castano (1). The body currently in use has a longer injection filter section, and this larger region of roughness may have resulted in a thicker layer. To make the LDV results self-contained, we shall measure the boundary layers for the zero pressure gradient case.

PLANS

LDV measurements of the boundary layer will be made for the zero pressure gradient case during our next tunnel entry.

The results and plans sketched above will provide the basis for a M. S. Thesis in Aerospace Engineering for Mr. H. Clark as well as for an additional publication.

REFERENCE

1. Deutsch, S. and J. Castano, Physics of Fluids 29, 3590 (1986).

SUBTASK DR3

Title: Turbulent Boundary Layer Modification by Suction (H. L. Petrie)

BACKGROUND

This project was supported by ONR in FY 87 and FY 88. FY 90 funds have recently become available to support one more experimental entry in the ARL Penn State 12-inch water tunnel in FY 90. This work is a continuation of the previous work and, for the most part, follows the initial plans.

Small amounts of wall suction reduce boundary layer turbulence substantially. Data presented to the sponsor and discussed in past annual reports have shown that suction coefficients, C_q, as low as -0.0001 can reduce turbulent boundary layer (TBL) RMS and Reynolds stress levels noticeably. The suction coefficient is the ratio of the velocity induced by suction normal to the surface to the freestream velocity. This has the potential benefit of TBL flow quieting.

Speculative explanations for the effects of wall suction on TBLs have been given. Suction may counteract the ejection velocity of lifting streaks of low momentum fluid or suction may stabilize the sublayer to delay and prevent bursting at the wall. To date, most research involving suction with turbulent boundary layers (TBLs) has used discrete spanwise slots or continuously porous surfaces to apply suction. The emphasis of many of these past efforts has been on heat transfer and skin friction changes with suction. Much of this past work was limited to mean velocity profile measurements or turbulence measurements at relatively high suction rates. Recent flow visualization and hot-wire work by Antonia, et al. (1988,1989) has examined the effects of suction on the structure of the TBL in greater detail. The flow visualizations support the premise that suction does stabilize wall streaks such that they oscillate less in spanwise direction and persist longer prior to lifting.

OBJECTIVES

The current research is directed at obtaining a detailed look at the characteristics of a minute suction modified TBL. Uniform suction has been studied because it merits interest given the emphasis of existing work on high suction rate conditions but, primarily, this data is to establish a baseline for comparison purposes. The comparison would be made with a TBL developing over a tailored suction surface. The tailored surface is an attempt to apply wall suction in a way that may be a more efficient means of TBL control than steady uniform suction.

The tailored surface consists of streamwise oriented rows of holes that are, ideally, 80 to 100 viscous wall units apart at the test velocity. This corresponds to the approximate mean spacing between the

low speed streaks found near the wall in TBL flows. The rows of suction holes should introduce some structure and order into the flow to stabilize the near wall flow beyond that of uniform suction. The effect is somewhat analogous to riblets. To date, a uniform suction surface has been studied under previous funding but a tailored surface not been tested and this is a main objective.

The measurements that we have made to date support some of what had been speculated about from the beginning of the project. That is, very small amounts of suction can have a dramatic effect on the turbulent normal and shear stresses and that wall suction may be effective for flow quieting. Measurements of surface pressure fluctuations have been proposed but have not been made. We will attempt these measurements.

Finally, the possibility that modest amounts of suction may be useful for control of disturbances in a distorted TBL flow such as streamwise oriented vortical structures that may arise due to protuberances or appendages is or interest. A limited evaluation of this possible feature of suction flow control will be attempted. However, one short 12-inch tunnel test is not sufficient to really pursue this in depth.

PROGRESS

The main piece of test hardware, a multi-plenum drag balance with the capability to accept porous surfaces with small flush mounted probes was modified at the end of the FY 88 funded period. These modifications addressed problems encountered in the previous testing. This was done in lieu of a tailored surface test because our attempts at a simple fix of some problems only made matters worse. The funds remaining would not support both fixing and testing. The sensing members of the drag balance have undergone improvements in sensitivity and zero drift since this work ended in FY 88 in support of another project.

Given that the FY 90 funds have just become available, plans for the continuation of this work have just begun. However, it is fully expected that our experiments will be completed by the end of summer.

PLANS

The experiments will take place within the next two quarters. In this next quarter, some new tailored and uniform suction skins will be fabricated. We are considering two tailored surfaces with row spacing appropriate for testing at 15 ft/s and at 5 ft/s. The porous surfaces are metal skins that are chemically etched in house. This is something that has been done for the project before and is now fairly straightforward.

The experiments will consist of drag balance measurements. LDV surveys, and surface pressure fluctuations measurements will be attempted. The small pressure transducers to be used are not likely to

survive very long and the pressure measurements may not be successful as a result. The viscous scales and the configuration of the hardware are such that visualization of near wall streaks over the suction surface is very difficult. Dye has to be seeped into the near wall flow on or immediately upstream of the suction surface and this is not possible.

Tailored and uniform suction at C_q from -0.0001 to -0.003 with freestream velocities of 5 and 15 ft/s will be studied. The case of a disturbed TBL flow will be examined at one velocity with one suction surface at three suction levels, if time allows.

REFERENCES

1. Antonia, R. A., Fulachier, L., Krishnamoorthy, L. V., Benabid, T., and Anselment, F., "Influence of Wall Suction on the Organized Motion in a Turbulent Boundary Layer," JFM, V190, 1988, pp. 217-240.

2. Antonia, R. A. and Fulachier, L., "Topology of a Turbulent Boundary Layer With and Without Wall Suction," JFM, V198, 1989, pp. 429-451.

DISTRIBUTION LIST

Office of Naval Research
800 North Quincy Street
Department of the Navy
Arlington, VA 22217
Attn: A. D. Wood, Code 12
R. J. Hansen, Code 1215
J. A. Fein, Code 1215
M. M. Reischman, Code 11
M. Orr, Code 11250A
E. P. Rood, Code 121132F

Office of Naval Research
Admin. Contracting Officer
The Ohio State University
Research Center
1314 Kinnear Road
Room 318
Columbus, OH 43212-1194
Attn: N. A. Meeks

Office of Naval Technology
800 North Quincy Street
Department of the Navy
Arlington, VA 22217-5000
Attn: A. J. Faulstich, Jr., Code ONT-234
D. C. Houser, Code OCNR-232
C. Votaw, Code OCNR-232

Naval Underwater Systems Center
Newport, RI 02840
Attn: D. J. Goodrich, Code 3634
D. A. Brown, Code 8214

University of Cincinnati
Department of Aerospace Engineering
Cincinnati, OH 45221
Attn: S. A. Abdallah

Applied Research Laboratory
The Pennsylvania State University
Post Office Box 30
State College, PA 16804
Attn: L. R. Hettche
M. L. Billet
S. Deutsch
R. E. Henderson
G. C. Lauchle
P. J. Morris
H. L. Petrie
R. Stern
FDT Files

Director
Naval Research Laboratory
Washington, DC 20375
Attn: Code 2627
(6 Copies)

Defense Technical Information
Center
Building 5
Cameron Station
Alexandria, VA 22314
(12 Copies)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		Quarterly 10/1/89-12/1/89

4. TITLE AND SUBTITLE
FUNDAMENTAL HYDRODYNAMICS RESEARCH

5. FUNDING NUMBERS
N00014-87-K-0196

6. AUTHOR(S)
Abdallah, S. A. and Billet, M. L. - Subtask T1
Petrie, H. L. and Morris, P. J. - Subtask DR1
Deutsch, S. - Subtask DR2

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Applied Research Laboratory
Penn State University
Post Office Box 30
State College, PA 16804

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy Street
Department of the Navy
Arlington, VA 22217
Attn: Code 1215

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified/Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)
Under the sponsorship of the Office of Naval Research (Code 12) AHR Program, the Applied Research Laboratory of Penn State University performs basic research in hydrodynamics and hydrodynamic noise. The hydrodynamics research conducted under this program falls into two basic thrust areas:

- Turbomachinery - To develop an improved understanding of the fluid mechanics and acoustics associated with low-speed turbomachines and marine propulsors. To employ this knowledge to the development of improved propulsor and turbomachine design methods.
- Drag Reduction - To develop fundamental understanding of the mechanisms that cause drag on bodies and surfaces and to explore novel methods to reduce drag.

Under each thrust area, one or more projects are conducted under the direction of the principal investigator who initiated the given task. All tasks are designed to provide results that will improve the scientific understanding of various hydrodynamic phenomena associated with the operation of submerged bodies and surfaces.

This report documents the technical progress realized during the first quarter of FY 90 for the projects currently approved under this program.

14. SUBJECT TERMS
turbomachinery, drag reduction, microbubbles, pressure gradients, particle trajectories, transition, computational fluids, unsteady 3-D flows, turbulent flow

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	